

Studying the interplay of strong and electromagnetic forces in heavy-ion collisions with NICA^{*}

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Abstract. In the following we stress the advantages of the NICA research programme in the context of studying the spectator-induced electromagnetic phenomena present in heavy-ion collisions. We point at the specific interest of using these phenomena as a new, independent source of information on the space-time evolution of the reaction and of the non-perturbative process of particle production. We propose an extended series of measurements of well-defined observables to be performed in different types of nuclear reactions and in the whole range of collision energies available to NICA. We expect these measurements to bring very valuable new insight into the mechanism of non-perturbative strong interactions, complementary to the studies made at the SPS at CERN, RHIC at BNL, and the LHC.

1 Introduction

The specific features of the NICA (Nuclotron-based Ion Collider fAcility) research programme [1], and in particular a) the broad range of reactions planned to be studied, b) the relatively modest collision energy $\sqrt{s_{NN}}$, placing the whole programme close to that of the CERN SPS, c) the possibility to measure reactions at different energies, and d) the elasticity of taking measurements both in fixed target and collider modes, make it well suitable for studying the interplay of strong and electromagnetic interactions in nuclear collisions. What we specifically address in the present proposal is the *electromagnetic interaction between charged particles produced in the collision and the nuclear remnant that does not participate directly in the reaction* (the “spectator system”). This latter phenomenon is of particular interest because, as discussed in our earlier works [2], *it provides independent information on the space time-evolution of the reaction*: the space-time evolution of the particle production process, the fragmentation (break-up) of the spectator system, and the interplay between the two. It is to be noted that with the well-known exception of HBT measurements [3, 4], the experimental programmes at the SPS, RHIC and LHC provide

direct information essentially only on the final (or near-to-final) state particles in *momentum space* (p_x, p_y, p_z). Much less is possible as far as providing information on the evolution of the reaction in *position space* (x, y, z), which, on the other hand, is extremely important in view of our understanding of the heavy-ion reaction. Here NICA could strongly contribute to the overall knowledge in the whole heavy-ion field, with very little competition from existing experiments. The corresponding measurements would in particular include *particle spectra*, *charged particle ratios* (π^+/π^- , K^+/K^- , etc.) and *directed flow*.

This paper is organized as follows. In sect. 2, we discuss the principal features of the spectator-induced electromagnetic effect (see fig. 1), with particular emphasis on its importance as a new source of information on the mechanism of the nuclear reaction. In sect. 3, we define the possible future contribution of NICA. In sect. 4, we shortly address the subject of competition from other experiments. We present our conclusions in sect. 5.

2 What do we know about the spectator-induced electromagnetic effect?

It is not surprising that various kinds of electromagnetic interactions in nucleus-nucleus collisions were studied in the past (a partial overview can be found in [5, 6]). The problem of Coulomb corrections to HBT measurements belongs in fact to the “standard” in the analysis of heavy-ion experimental data. Numerous works exist also on the

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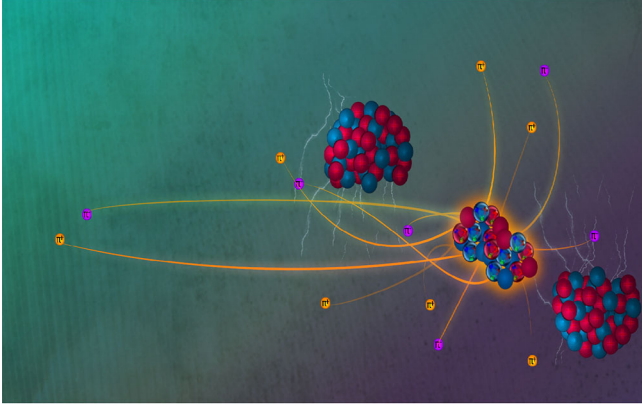


Fig. 1. The general idea of the spectator-induced electromagnetic effect discussed in this paper. The figure is redrawn from [7].

influence of the electromagnetic field on the spectra of particles produced at *mid-rapidity* (that is, in the vicinity of $x_F = 0$) in central heavy-ion reactions¹ [8–11]. However, these concentrate on the electromagnetic field induced by the presence of initial charge in the participant zone, that is, the charge of the *participating nucleons*². On the other hand, it seems that the theoretical and experimental analyses of the electromagnetic interactions between *nuclear remnants* and produced particles were performed mostly at lower energies. Very sizeable electromagnetically induced distortions were observed there [12, 13]. An important, much more recent result, was reported in nuclear collisions at several GeV/nucleon, where the non-relativistic approach to the Coulomb field brought information on the space-time evolution of the process of nuclear fragmentation [14]. In the energy regime of the CERN SPS and above, up to now our main range of interest, we were aware of only one earlier experimental measurement [15]. The latter was unfortunately restricted to a very narrow acceptance range (forward angles *i.e.* $p_T \approx 0$), and to an extremely small number of data points (between two and four, depending on collision centrality) which limited its scientific usefulness. For this reason, we performed a series of experimental and theoretical studies of the influence which the spectator charge exerts on charged pion and charged kaon spectra³ [2, 7, 16–19]. Out of these, a consistent picture emerges which can be summarized as follows.

¹ We always define the Feynman $x_F = \frac{p_L}{p_L(m_{ax})}$ and rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_L}{E-p_L} \right)$ in the nucleon-nucleon c.m.s.

² Note: the two electromagnetic effects discussed above, namely that induced by the participant and by the spectator charge, should be clearly differentiated as they have a different distribution over phase-space and a different centrality dependence. The participant charge will mostly influence the region closer to $x_F = 0$ in central nucleus-nucleus collisions, see above, while the spectator charge will produce the largest effect at higher values of x_F and in peripheral collisions.

³ All the experimental results were obtained within the framework of the NA49 experiment at the CERN SPS (see [20] for a detailed description of the NA49 detector).

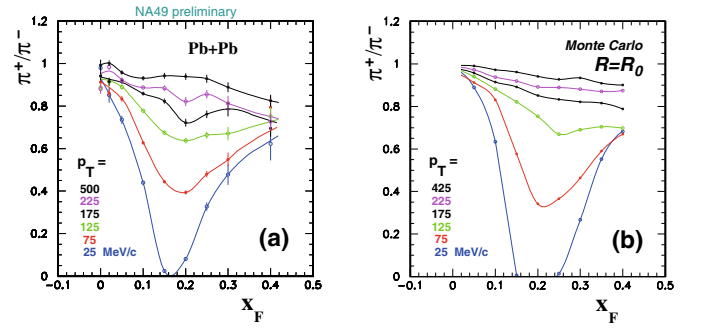


Fig. 2. Electromagnetic distortion of charged-pion ratios in the projectile hemisphere of the peripheral Pb+Pb reaction. (a) The π^+/π^- ratios measured by the NA49 experiment at the CERN SPS, drawn as a function of x_F at fixed values of p_T (listed from top to bottom curve). (b) Result of the Monte Carlo simulation described in the text. Figure taken from [19].

- 1) The presence of the spectator-induced electromagnetic field brings a very sizeable distortion to π^+/π^- ratios observed in the final state of peripheral (large impact parameter) Pb+Pb reactions measured at a beam energy of 158 GeV/nucleon ($\sqrt{s_{NN}} = 17.3$ GeV). This is shown in fig. 2(a), where the x_F -dependence of π^+/π^- ratios is drawn in the projectile hemisphere of the reaction, for fixed values of pion transverse momentum p_T . This effect is so strong that the π^+/π^- ratio goes close to zero in the vicinity of $x_F = 0.15$, violating isospin symmetry and thus unequivocally confirming the electromagnetic origin of the whole phenomenon. Note that the latter value of $x_F = 0.15 = m_\pi/m_N$ corresponds, at low transverse momenta, to pions moving at the same velocity as the spectator system, thus confirming that electromagnetic repulsion (attraction) of positive (negative) pions from positively charged spectator protons is indeed at the cause of this behaviour.
- 2) Our simple Monte Carlo model of the electromagnetic interaction [2, 16] brings a very reasonable description of the main features of this effect as shown in fig. 2(b). The unique region where a more significant disagreement between data and model can be seen ($x_F \approx 0.2$, low p_T) has been identified as due to the process of *nuclear fragmentation (break-up) of the spectator system*; a discussion of this subject can be found in [18].
- 3) A very similar electromagnetic effect is also present in high-energy collisions of lead ions with lighter nuclei which we recently investigated [7].
- 4) The electromagnetic distortion observed in fig. 2(a) depends on the specific space-time scenario imposed on pion emission. This is illustrated in fig. 3 (left) where the results of our model calculations are drawn in the full range of x_F , $-1 < x_F < 1$, for different values assumed for the time of pion emission⁴ t_E . The characteristic distortion pattern imposed by the two spectator systems at positive and negative x_F appears clearly sensitive to t_E (with typically lower π^+/π^- ra-

⁴ Note: we define the time of pion emission with respect to the moment of closest approach of the two colliding nuclei [2].

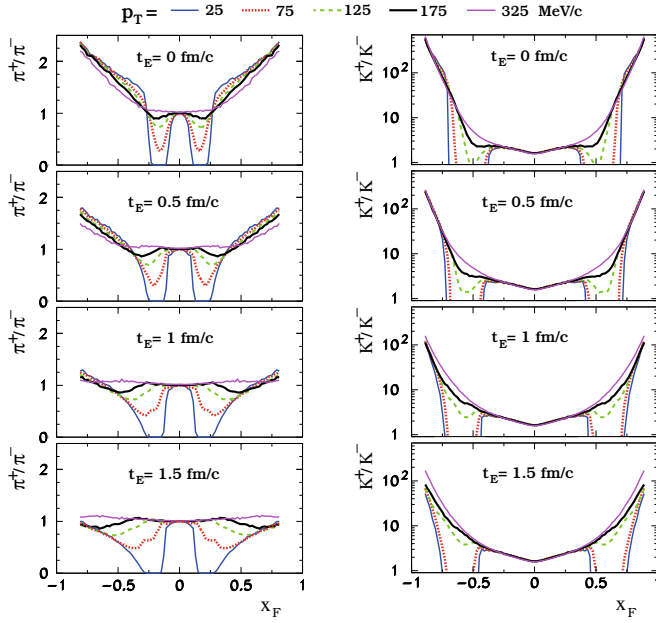


Fig. 3. Dependence of the electromagnetic distortion of π^+/π^- (left) and K^+/K^- (right) ratios, for particles produced in peripheral Pb+Pb collisions. The different panels correspond to different pion and kaon emission times t_E . Figure taken from [19].

tios obtained for larger t_E at higher values of x_F . This implies that the electromagnetic effect provides independent information on the evolution of the non-perturbative process of pion production in space and time [2, 16].

- 5) The electromagnetic distortion of charged kaon (K^+/K^-) ratios, fig. 3 (right), exhibits basic qualitative similarities to the effect seen for pions, however, with pronounced differences on the quantitative level. The position of the deep valley in the ratio is displaced towards higher values of x_F , and the region of highest sensitivity to the kaon emission time is moved towards very high x_F ($x_F > 0.75$).
- 6) Finally, as apparent in fig. 4, the spectator-induced electromagnetic force exerts also a noticeable influence on pion directed flow, v_1 . Our very recent Monte Carlo calculation [21] predicts a well-defined pattern in the rapidity dependence of the electromagnetically induced directed flow of positive pions, with a large peak in the vicinity of projectile and target rapidities. As such, directed flow of charged pions (π^+ , π^-) appears as another observable where, also through electromagnetic effects, new information on the space-time evolution of the reaction can become available.

The above description is, of course, highly simplified (the interested reader is invited to visit the enclosed bibliography for a more detailed account), but nevertheless constitutes a good starting point for the present proposal. As it comes from the considerations above, and as has also been suggested to us in numerous discussions with experts, the spectator-induced electromagnetic effects dis-

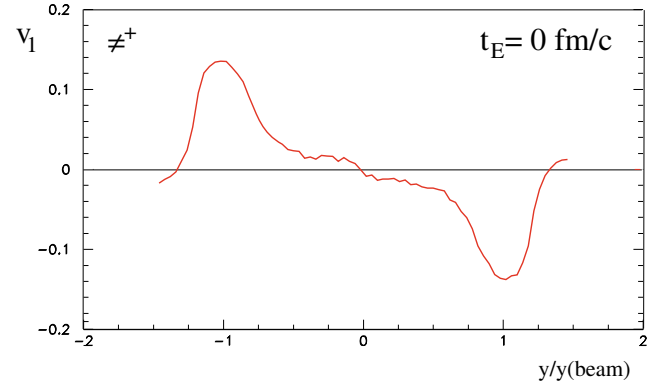


Fig. 4. Dependence of the electromagnetically induced directed flow of positively charged pions on the scaled pion rapidity $y/y(\text{beam})$. The simulation assumes the pion emission time t_E equal to zero. Directed flow is integrated over p_T from 0 to 1 GeV/c.

cussed here have very specific characteristics which make them attractive for numerous future studies:

- they can be large in specific regions of phase space;
- they can bring large distortions to various collision characteristics observed in the final state (like charged particle ratios or directed flow) and at the same time, they can provide information about the intrinsic space-time scenario of particle emission (formation times, parton fragmentation, resonance decays, hydrodynamics, etc.).

As such, in principle they should be studied in any possible reaction at any possible energy, whenever this is possible. This is particularly important in the present situation where the available experimental information remains very limited. In the high-energy regime (SPS and RHIC BES energies and above), no experimental data set other than what was discussed above is known to us, with the exception of charge-dependent v_1 measurements [22] which we discuss in [21, 23] as another evidence for spectator-induced EM effects. No possibility of obtaining comparable information at the LHC is apparent to us due to strict experimental limitations. For this reason, we see here a good scientific prospect for NICA.

3 Possible measurements at NICA

The principal detector requirements needed in order to perform measurements of the spectator-induced electromagnetic effect are particle momentum vector reconstruction and particle identification capabilities (including in particular charge differentiation), as well as a relatively wide acceptance coverage defined in terms of longitudinal and transverse momenta. Once these conditions are fulfilled, measurements of particle spectra (preferably double differential spectra of the type $\frac{d^2n}{dy dp_T}$) become accessible. Measurements of directed flow (as well as possibly higher harmonics) are characterized by additional requirements well known to the community.

In the range of collision energies specified in [1], the NICA/MPD apparatus looks promising in view of the requirements specified above. With the extremely broad spectrum of reactions planned to be analysed, including in particular proton-nucleus and nucleus-nucleus collisions with an impressive versatility of projectiles and targets, we propose a *detailed, systematic experimental study of charged-particle spectra and directed flow with a special emphasis on charge asymmetries induced by electromagnetic interactions*. Such a very broad study, taking full benefit of the possibility of cross-comparisons between different reactions (in particular also proton-nucleus collisions), of switching between fixed target and collider modes with different ranges of effective acceptance in both cases, and of comparisons of different collision energies, would in our view provide new information on the *space-time evolution of very different aspects of nuclear reactions*. In particular, these would be

- the centrality and system-size dependence of particle production phenomena;
- the interplay between particle production and spectator fragmentation;
- azimuthal anisotropies and flow;
- the energy dependence of particle production.

All of the above are clearly basic, essential issues in heavy ion collision physics. With the advent of the NICA research programme, these could be analysed also with full use of the specific electromagnetic interaction as discussed in the present proposal.

4 Competition from existing experiments

As already specified above, we consider the competition from existing experiments as relatively weak with respect to the possibilities offered by NICA and its experimental community. We see at present no LHC experiment to be able to provide comparably reliable measurements of the phenomena discussed here. What remains is clearly the SPS and RHIC BES energy range where, as evident from the results presented in fig. 2 above, new experimental analyses can be performed on the basis of data from the NA49 experiment [20] or from its extension, NA61/SHINE [24]. New measurements from STAR could also possibly be expected. This could make these experiments complementary to NICA/MPD, but with specific limitations which would require a more in-depth study.

5 Conclusions

The interplay of strong and electromagnetic interactions in nuclear collisions, including in particular the spectator-induced electromagnetic distortion of charged-particle spectra and azimuthal anisotropies, constitutes a new, and in our opinion, very promising source of information on the space-time evolution of various processes present in the heavy-ion reaction. The range of collision energies considered for NICA, together with its experimental elasticity in

terms of data taking mode and of the versatile choice of interacting projectiles and targets, makes it in our opinion well suitable to bring a very valuable contribution to studies of this phenomenon.

The here presented estimates have been done with a very simplified model. However, the model parameters can be adjusted to describe existing SPS data (ref. [19] and fig. 2). We currently work on a more realistic model of initial conditions for the low energies. So far the electromagnetic effects were simulated based on initial conditions obtained from Hijing [25] and hadron string dynamics [26]. We hope for a comparison of results for different model initial conditions in the future.

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